# Asteroid Defense Modeling

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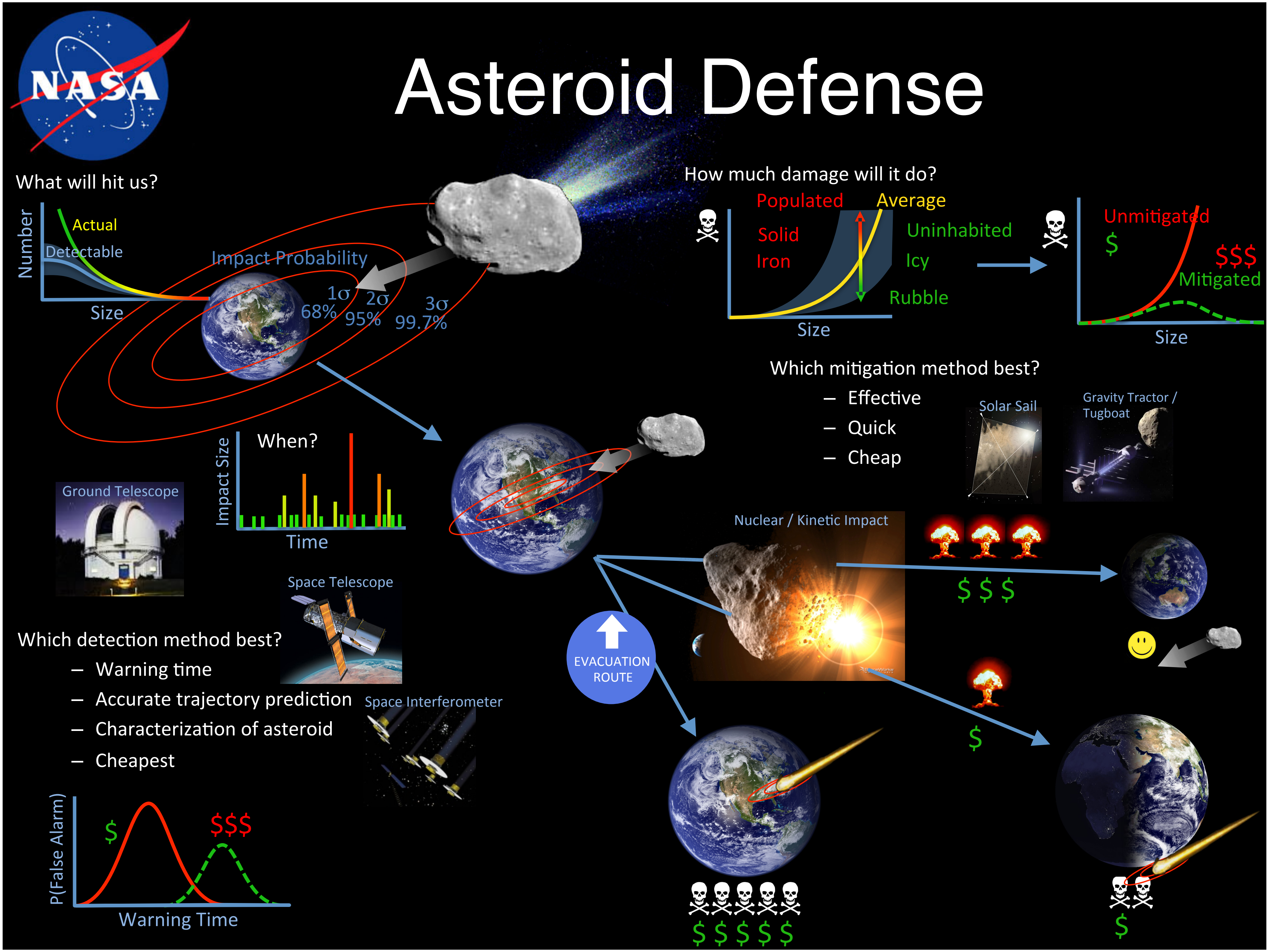
# Asteroid Sizes

L.A. vs Churyumov-Gerasimenko (ESA Rosetta lander 2014)

Duende Chelyabinsk

Paris vs. Itokawa
(Japanese sample return 2005)

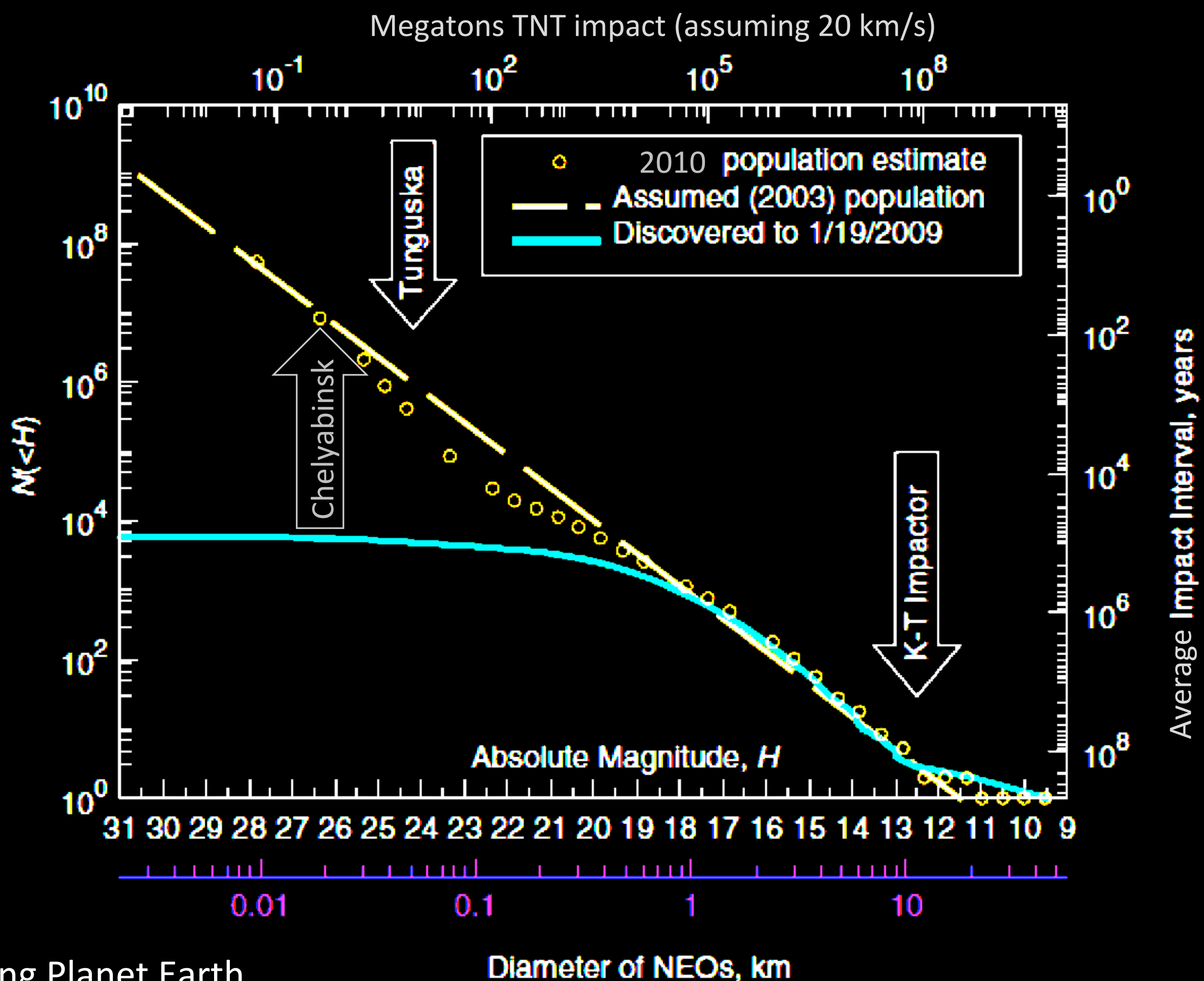
- Duende (2012 DA14) passed closer than GEO
- Chelyabinsk Meteor (estimated size)
    - 1500 people hospitalized mostly due to broken glass



NASA
Asteroid Defense
What will hit us?
Number
Actual
Detectable
Size
Impact Probability
1σ
68%
2σ
95%
3σ
99.7%
How much damage will it do?
Populated
Average
Solid
Iron
Uninhabited
Icy
Rubble
Size
Unmitigated
$
$$$
Mitigated
Size
Which mitigation method best?
– Effective
– Quick
– Cheap
Solar Sail
Gravity Tractor / Tugboat
Impact Size
When?
Time
Ground Telescope
Nuclear / Kinetic Impact
$ $ $
Space Telescope
Which detection method best?
– Warning time
– Accurate trajectory prediction
– Characterization of asteroid
– Cheapest
EVACUATION ROUTE
Space Interferometer
$
P(False Alarm)
$
$$$
Warning Time
$ $ $ $ $
$

# Near Earth Objects

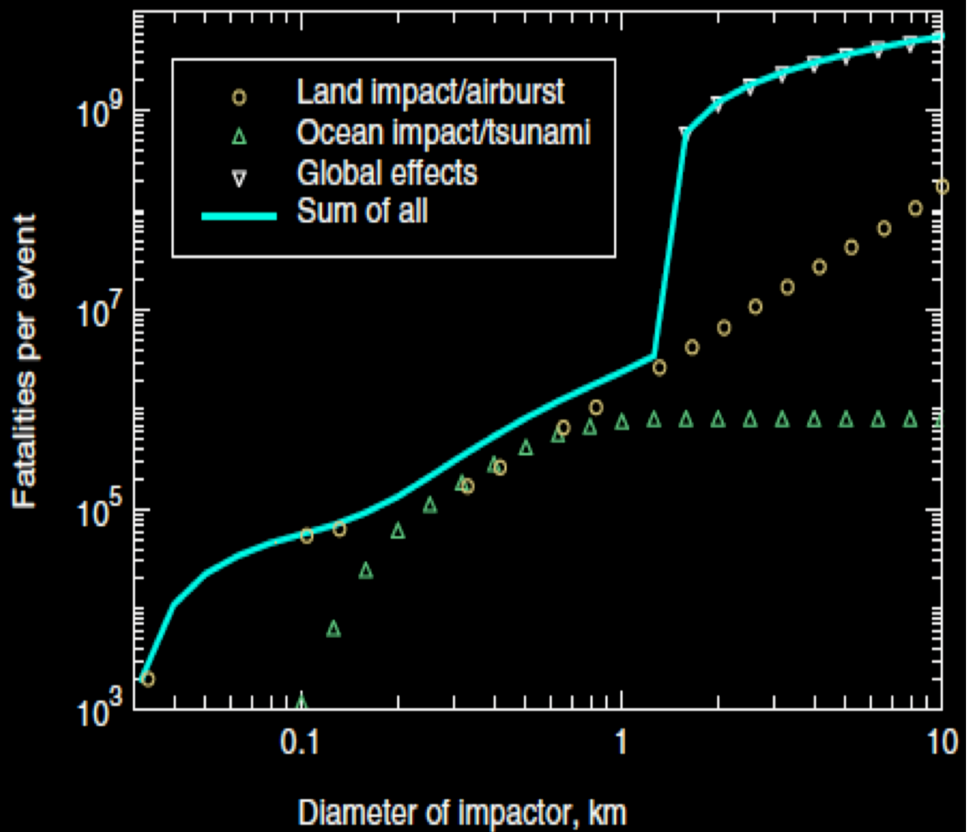
- Does not include comets and other long-period Earth crossing objects!
- Comets often have Trans-Neptune aphelion
- Speeds up to ~80 km/s




NRC 2010 - Defending Planet Earth

# Estimated Effects

| Type of Event | Typical Diameter | Average Impact Energy (MT) | Average Interval (yrs) |
|---|---|---|---|
| Airburst | 25 m | 1 | 200 |
| "City Killer" | 50 m | 10 | 2000 |
| Regional catastrophe | 140 m | 300 | 30 000 |
| Continental catastrophe | 300 m | 2000 | 100 000 |
| Global catastrophe | 1 km | 100 000 | 700 000 |
| Mass extinction | 10 km | 100 million | 100 million |




- Impact energies can vary significantly with NEO composition and trajectory
- Probability of large strike in near future very small, but consequences very severe.
- We have the capabilities to detect and mitigate most Near Earth Object threats

NRC 2010 - Defending Planet Earth

# Chelyabinsk

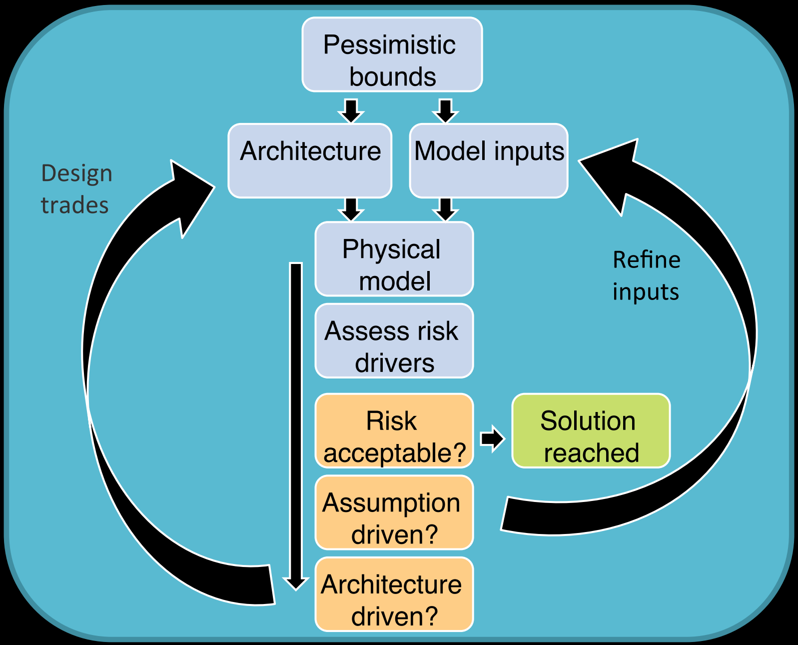

- 19.16 ± 0.15 km $s^{-1}$
- Entry angle 16° to horizon
- Airburst began at 29.7km
- Estimated Ø20m, 12 tonnes
- ~500 kT TNT = 25 Hiroshima size atomic bombs
- Ø1m fragment recovered from Lake
- Ordinary Chondrite w. 10% iron
- 1500 injuries mostly from broken gl (20 bassurns from radiation)
- 7000 buildings damaged
- Chelyabinsk city population 1.1M
- What if iron meteor or near vertical entry directly over city?

# Why model impacts?

- Current state of the art simulations suggest impacts especially at the “City Killer” size are significantly more damaging than previously estimated!
- Physical mechanisms of airburst unknown. Several theorized but none compared to experiment.
  - Pure mechanical failure
  - Flashing of trapped volatiles
  - Combustion of ablated material
- Determining best estimates of threat and sensitivity to variables can help in decision making of trade-offs of detection and mitigation strategies.

# Risk-Informed Decision Support

- Probabilistic Risk Assessment (PRA) provides quantitative evaluation of risk levels, drivers, and mitigation options
- Asteroid defense problem involves many high uncertainties
  - Characterization: numbers, sizes, compositions, etc.
  - Impact: level of threat various types of asteroids could pose
  - Mitigation: how well various defense strategies could reduce key threats
- Risk-informed decision support:
  - Risk assessment determines sensitivity of risk to key uncertain parameters
  - Enables resources to be allocated intelligently and efficiently

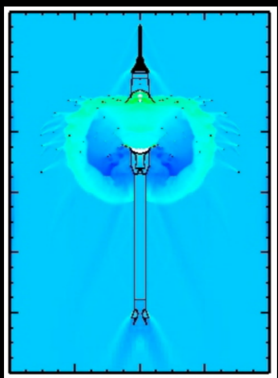



- Applications to multiple aspects of asteroid defense:
  - What level of defense system is warranted by the level of risk?
  - What asteroid/threat characteristics drive greatest risks?
  - What type of defense systems would most effectively/efficiently mitigate those risks/characteristics?

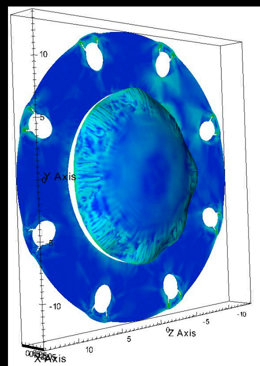
*PRA provides value by providing quantitative answers to specific questions*

# Physics-Based Risk Analysis Capabilities (Images)

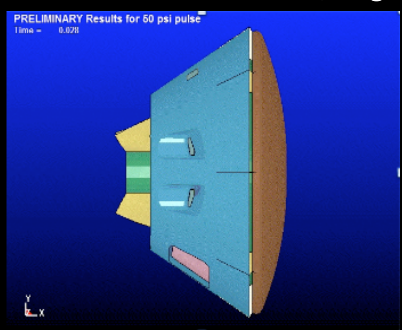
## Breakup



CTH Ares vehicle breakup simulations

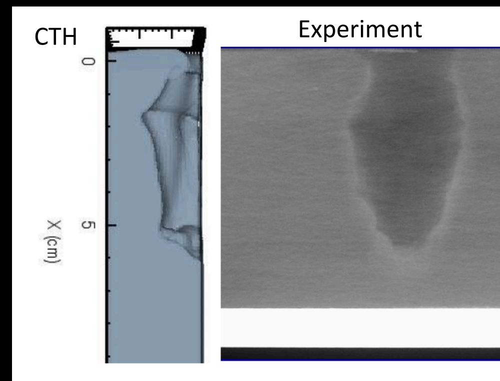


ALE3D tank plate burst/fragmentation

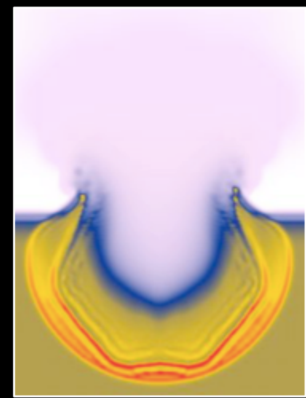



LS-DYNA Apollo capsule structural response

## Impact

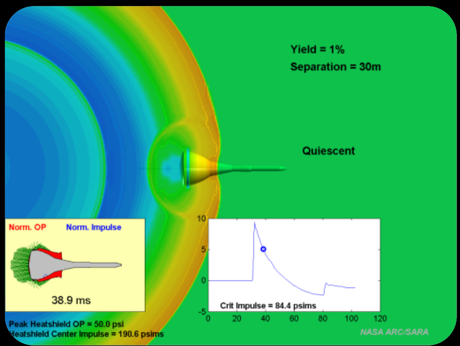



CTH simulation of hypervelocity impact into PICA TPS

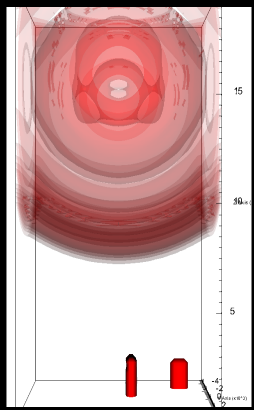


Hydrocode and Particle-in-Cell simulations of Plasma/ EMP generation from high-velocity meteoroid impacts

## Blast Propagation




OVERFLOW simulations of blast wave propagation and interaction



ALE3D simulation of tank air-burst over ground structures

# Compositions

- Iron meteorite ~6% of meteorites
  - Fe-Ni alloys: Kamacite (5–10% Ni, 90–95% Fe) or Taenite (20–65% Ni)
  - Solid with little void space

- Stony-Iron meteorites
  - Olivine ($Mg_2SiO_4$) in Fe-Ni matrix
- Chondrites (Stony) ~75% of meteorites
  - Fe-Ni (0–20% by mass), Olivine ($Mg_2SiO_4$), Bronzite (Mg 88%,Fe 12%)$SiO_3$, Pyroxene $XY(SiAl)_2O_6$ X=Fe,Mg Y=Al,Fe,Mg
  - Porosity ~10% but up to 60%, round grains (chondrules)

- Carbonaceous Chondrites ~5%
  - Fe-Ni, Magnetite ($Fe_3O_4$), Sulfates ($FeSO_4$, $Fe_2(SO_4)_3$, $MgSO_4$) , Ice (0–20%), amino acids, polycyclic aromatic hydrocarbons.
  - Porosity ~25%

- Achondrites ~8%
  - Same as chondrites but basalt texture due to melt/recrystallization
- Comets
  - Silicates (Stony) ~25%, $H_2O$ ~30%, Carbonaceous volatile ~10%, Carbonaceous non-volatile ~25%, other ices ~10% (CO, $CO_2$, methane, ammonia)
  - Highly porous. Speeds up to 80 km/s (often from Trans-Neptune aphelion)

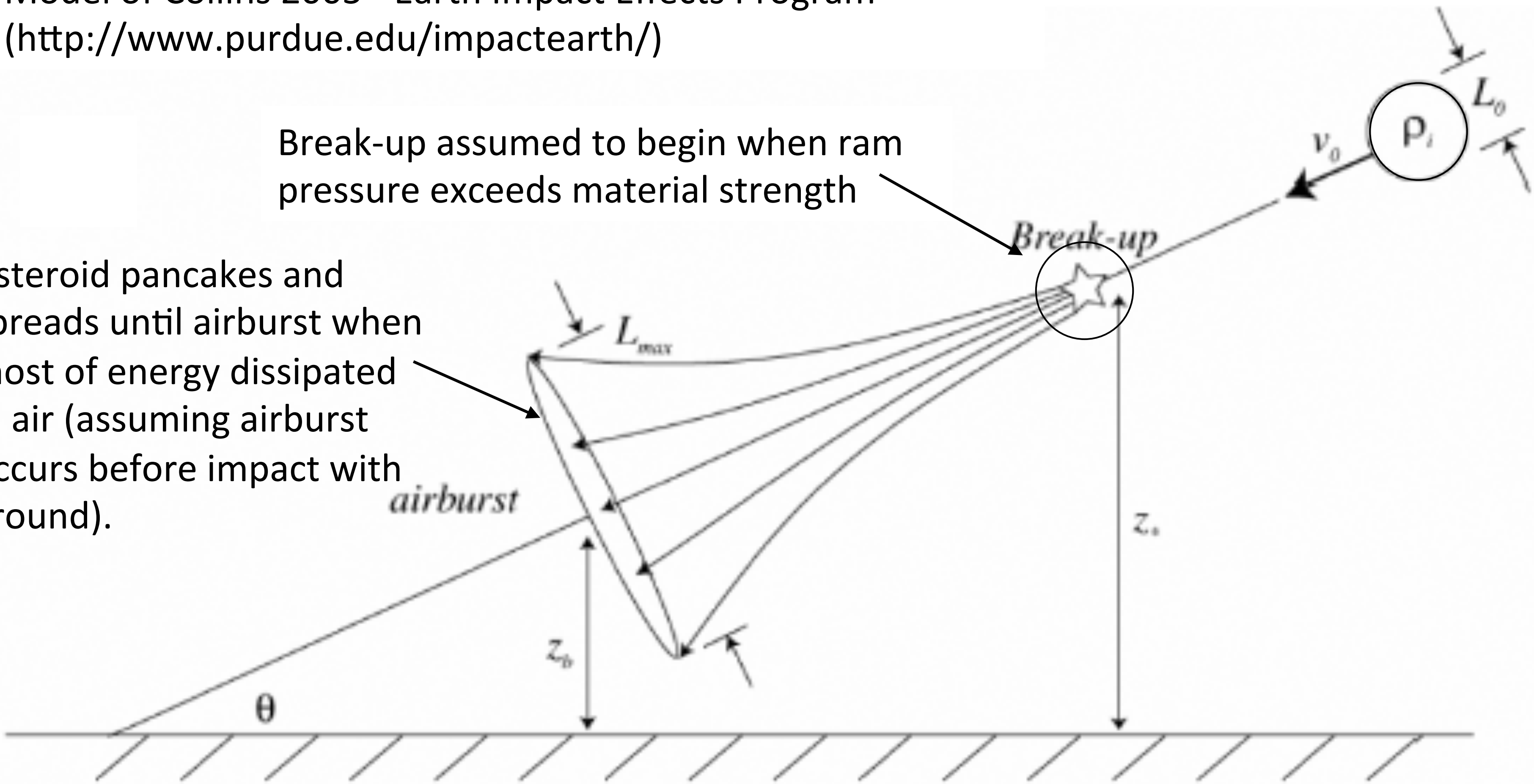
Permafrost core

# Simple Break-Up Models

Model of Collins 2005 - Earth Impact Effects Program (http://www.purdue.edu/impactearth/)

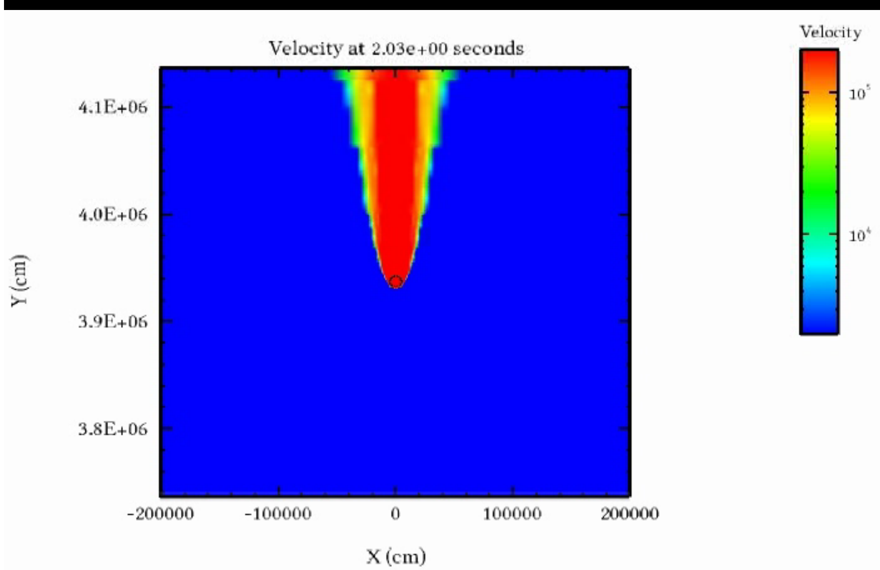
Break-up assumed to begin when ram pressure exceeds material strength

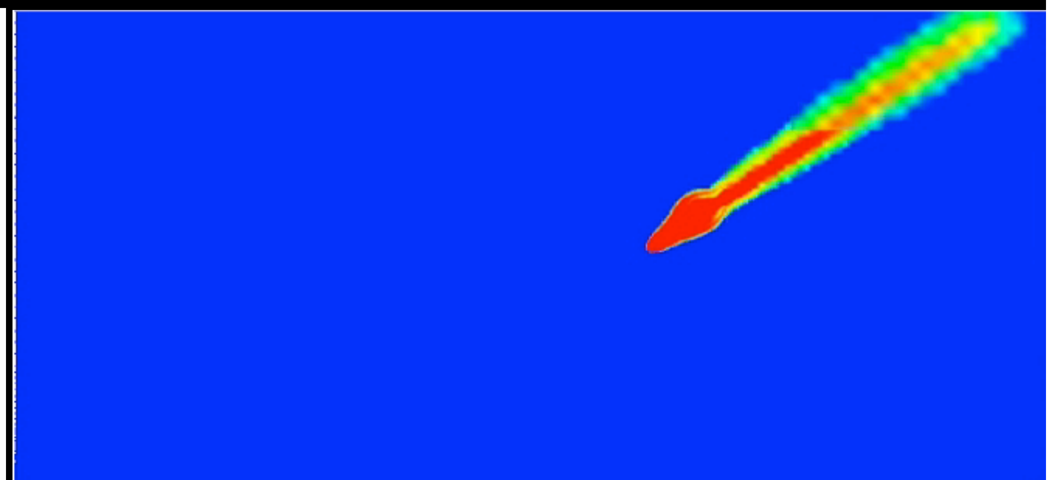
Asteroid pancakes and spreads until airburst when most of energy dissipated in air (assuming airburst occurs before impact with ground).



# Impact Energy Estimates

- Estimates of impact energy from observed damage vary widely. Tunguska estimates vary from 3 – 700 MT, with 10 – 40 most widely quoted.
- Yields typically derived from comparison to nuclear detonations. Boslough 2008 showed the downward momentum transferred by the asteroid significantly increased the damage compared to a static burst: e.g. a 3 MT burst was sufficient to create Tunguska-like damage.



- Caveat: Simulations forced an instantaneous vaporization airburst and did not model the physics of the burst.

Boslough 2008 – Low altitude airbursts and the impact threat

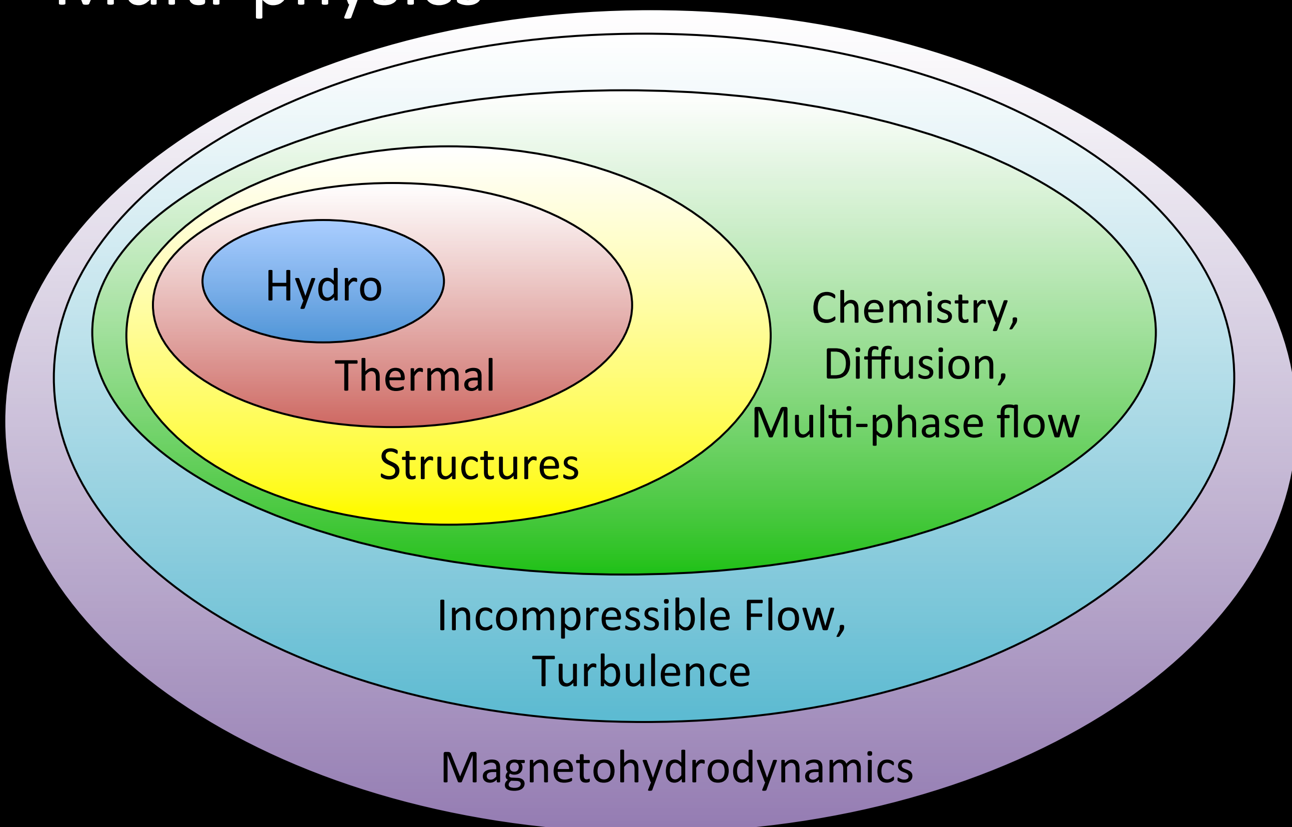
# Airburst Mechanisms

- Mechanical break-up
  - – Tensile, bending, compressive strengths exceeded
  - – Due to cracks, strength of rock typically decreases with size => break-up will occur in stages as fragments more resistant to further break-up

Baldwin 1971 – Ablation and break-up of meteoroids during entry

# ALE3D

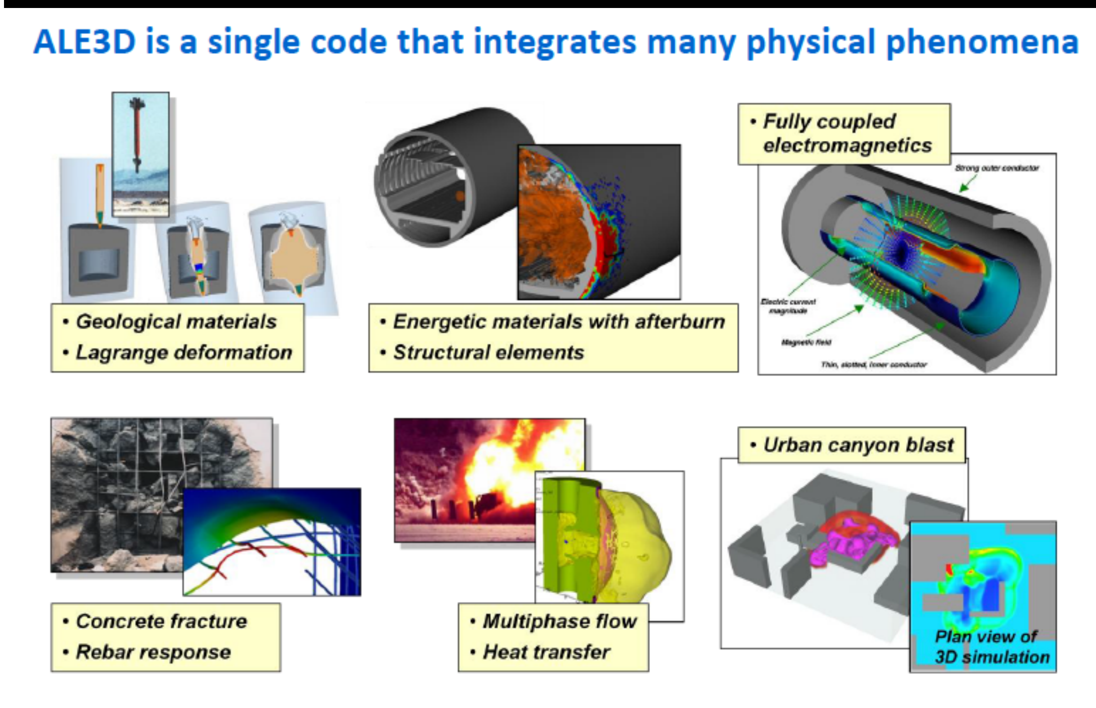
- Developed by LLNL
- Arbitrary Langrange Eulerian
- Multi-physics




- Explicit/Implicit time integration
- Multi-phase
- Element erosion
- Smooth particle hydrodynamics
- Overset grids
- Parallelized
- Unix/Windows

https://wci.llnl.gov/codes/ale3d/about_ale3d.html

# ALE3D

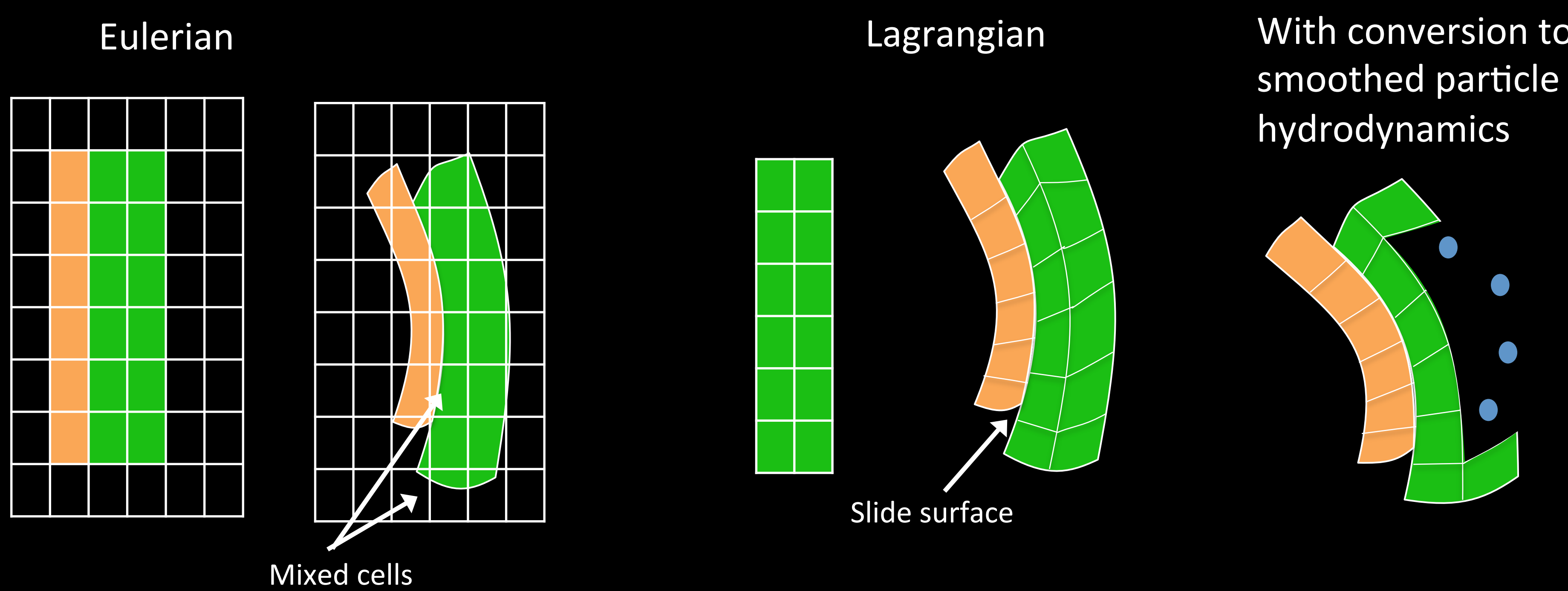


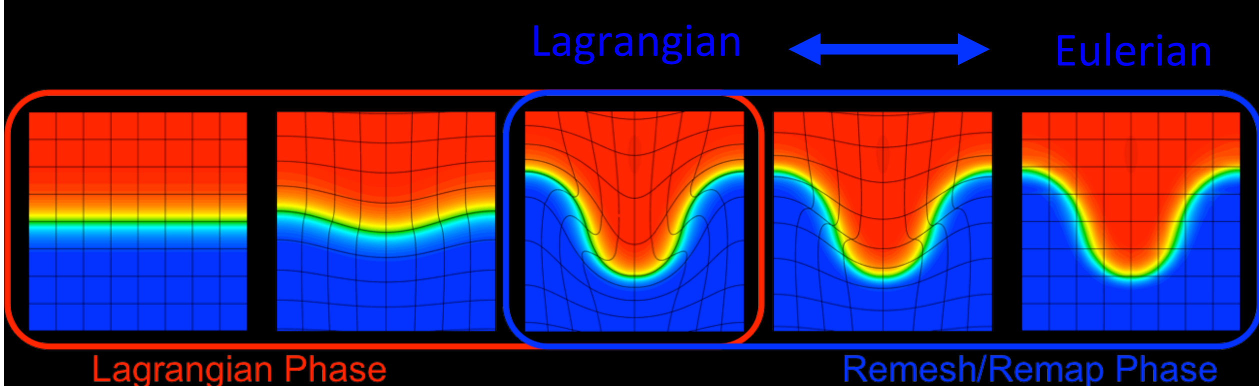

Applications useful to asteroid impact modelling

- hydrodynamic ram
- multi-phase flow
- Incompressible flow
- blast loading of structures
- aero-structural effects
- penetration mechanics
- non-eroding deformable penetration

https://wci.llnl.gov/codes/ale3d/about_ale3d.html

# ALE3D methods




- ALE allows mesh to follow material but relax when needed to reduce distortion

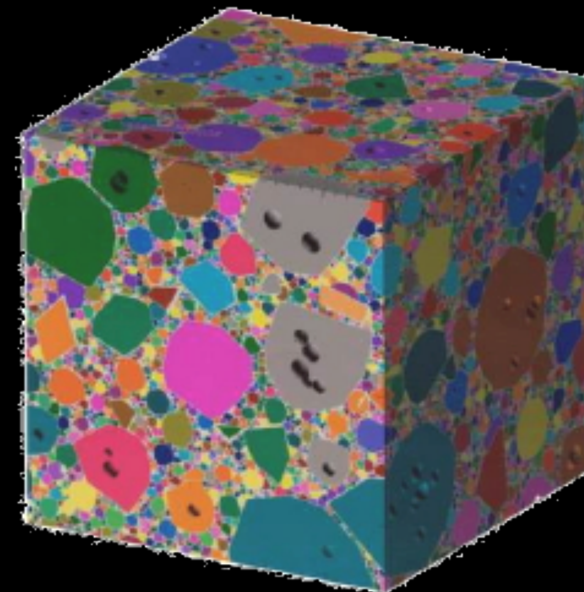
# Material Models

- Many material models:
- Equations of state
- Stress-strain models
- Anisotropy
- Fracture/Failure/Damage models
- Voids
- Chemistry and phase change

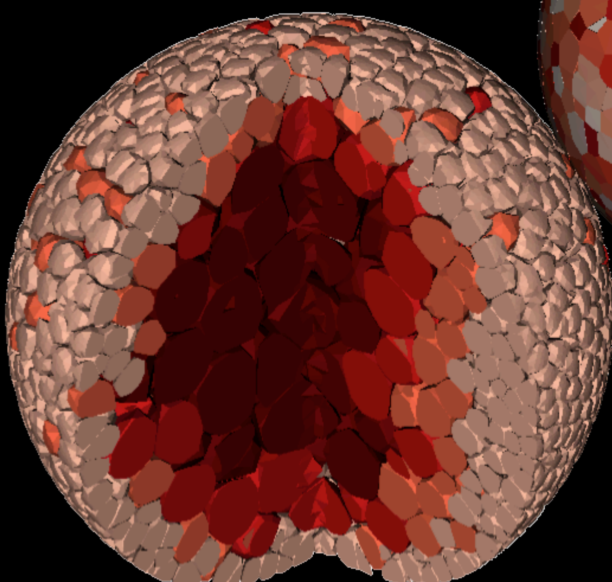
# Mesh Generation

- Internal Mesher for simple geometries
- Truegrid (XYZ Scientific)
- Cubit (Sandia National Lab)

# Particle Pack



Fractured Body



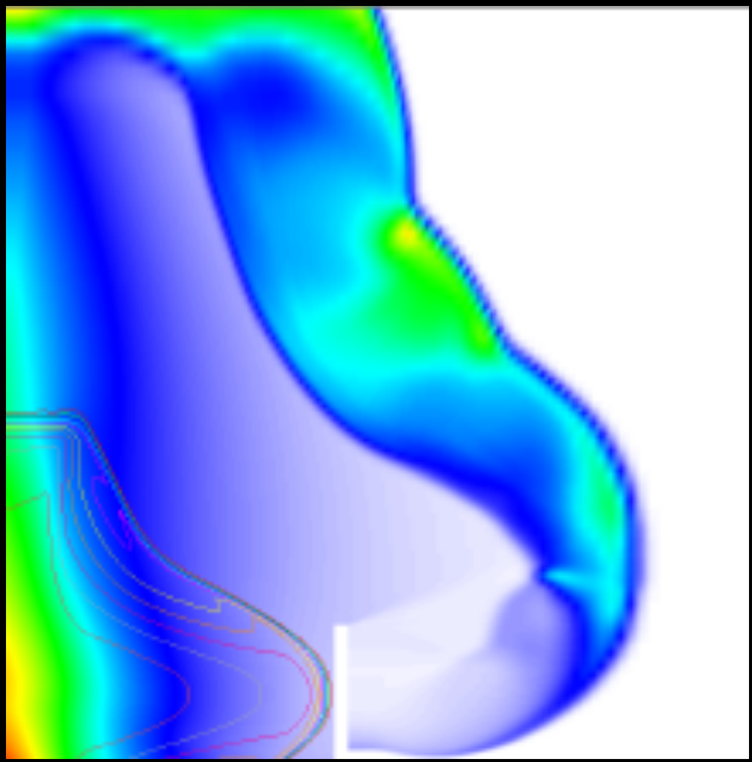
Gravitational Aggregate

**Application to Asteroid**

- Inhomogenous materials
- Grains of varying sizes and shapes
- Inhomogenous fracture strength
- Voids
- Automated generation and meshing

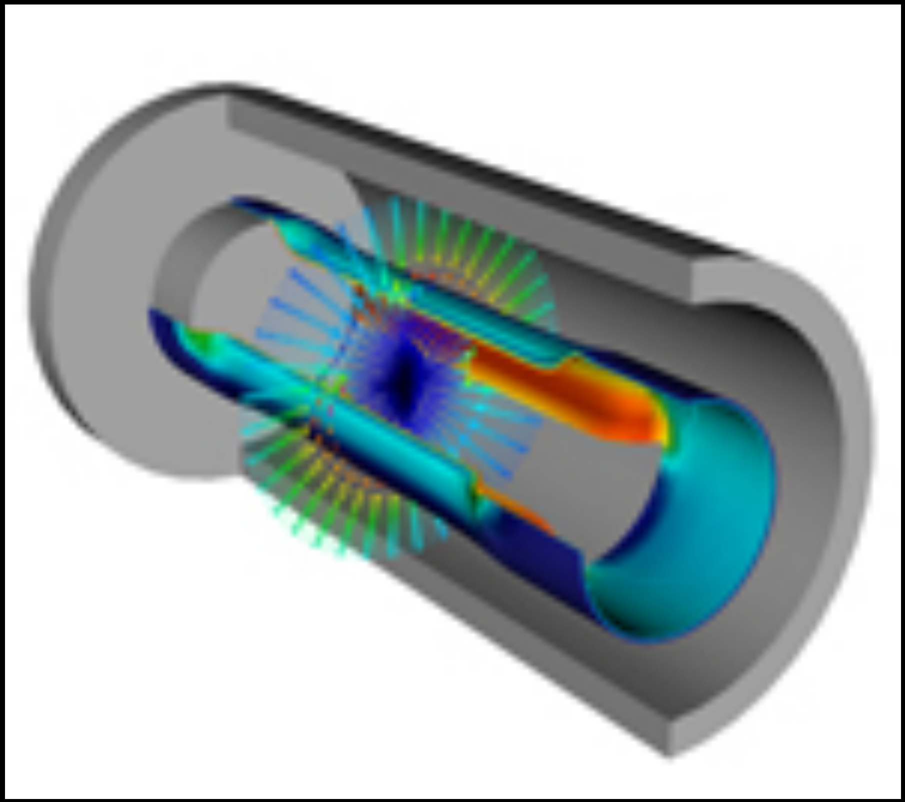
# Two-Phase Flow

- Hydrodynamically driven particles
- Ablation
- Afterburning
- Shock-induced mixing of gases and solids
- Complex EOS



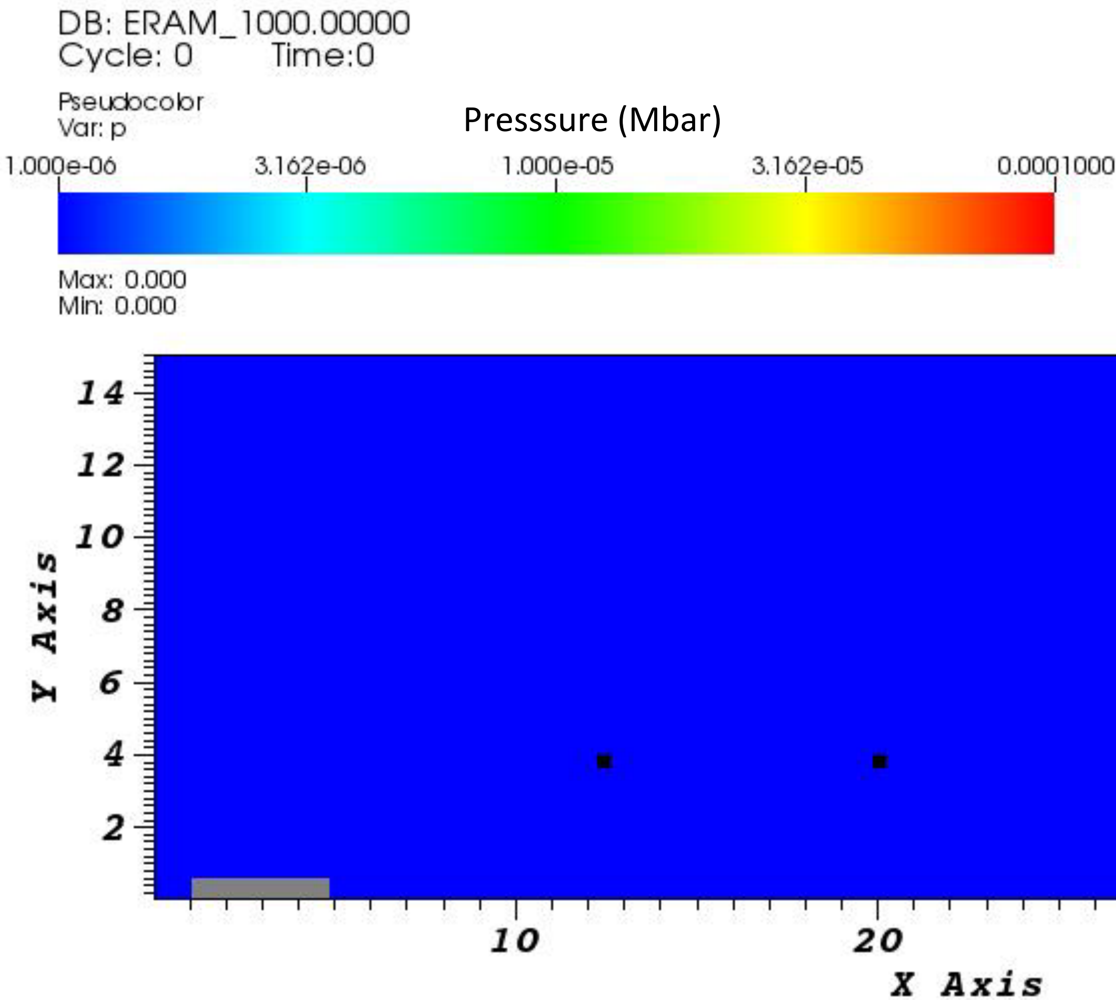
# MHD

- Magneto-Hydrodynamics (MHD)
- MHD module solves the transient magnetic advection-diffusion equation, magnetic forces are coupled to hydrodynamics and Joule heating is coupled to heat transfer.



# ERAM test

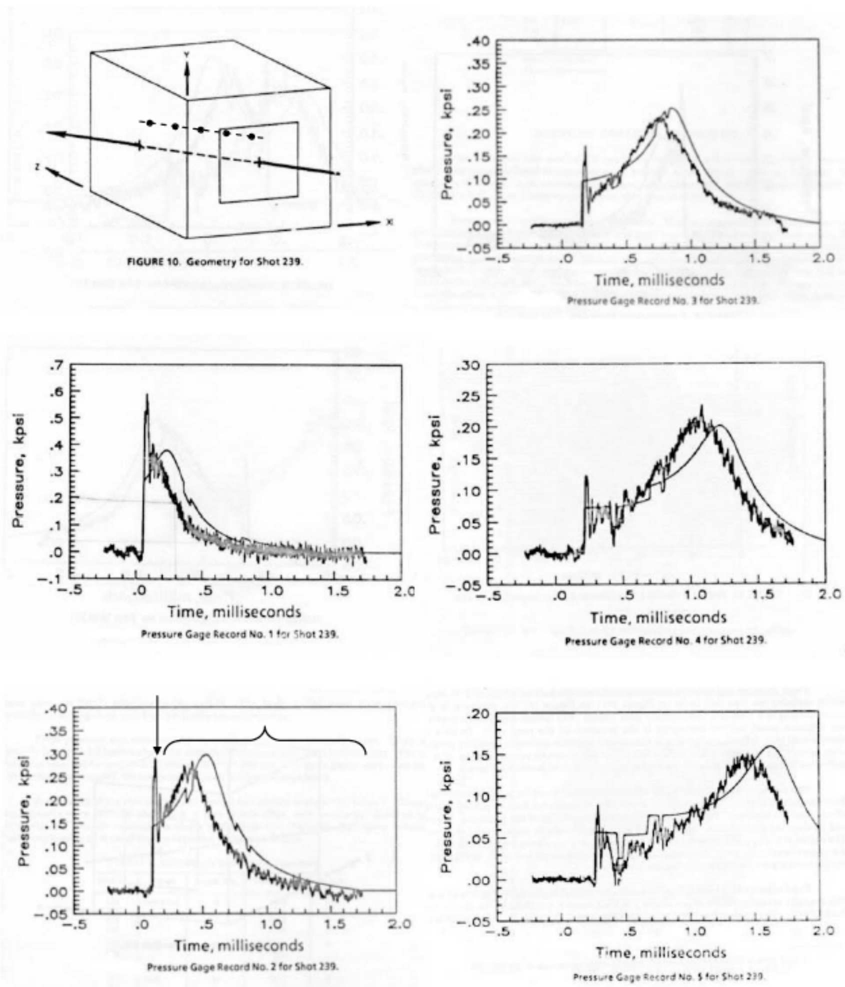
- Hydrodynamic ram of steel cylinder through water



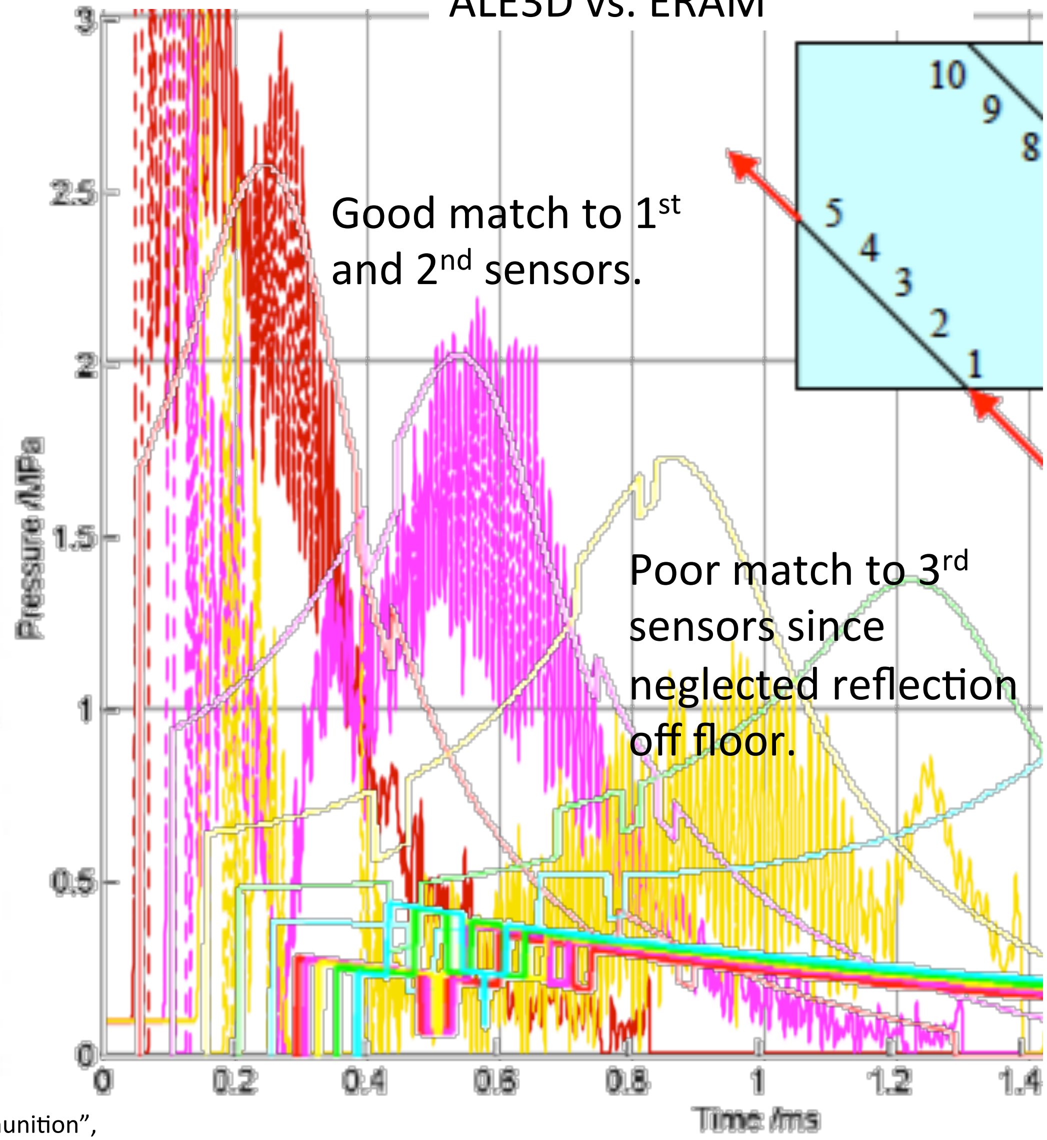

- Experiment used a tank of water with thin walls except thick concrete floor and back.
- ALE3D – neglect all walls and do axisymmetric simulation

# ERAM test

Experiment vs. ERAM simulation

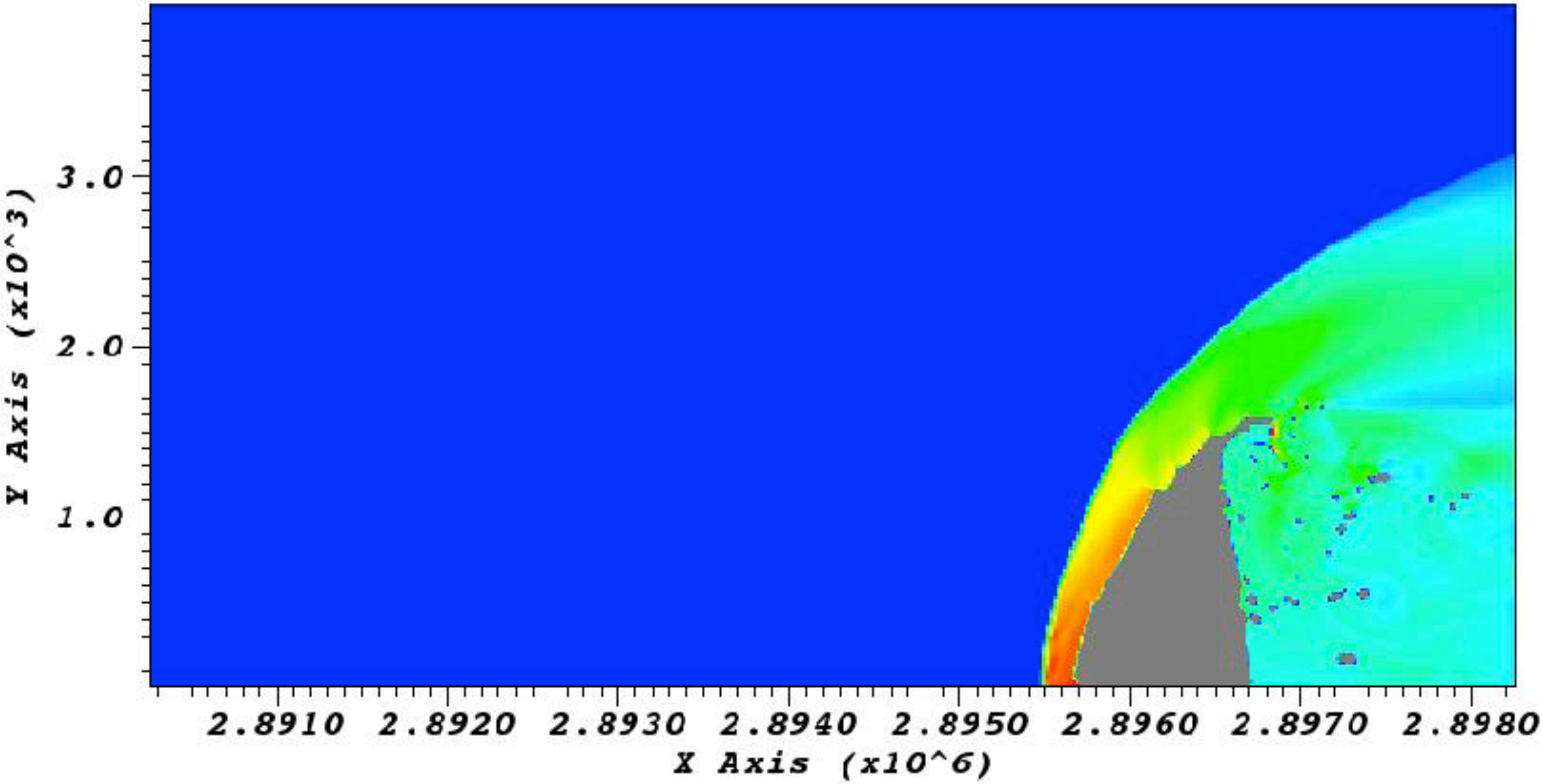



ALE3D vs. ERAM



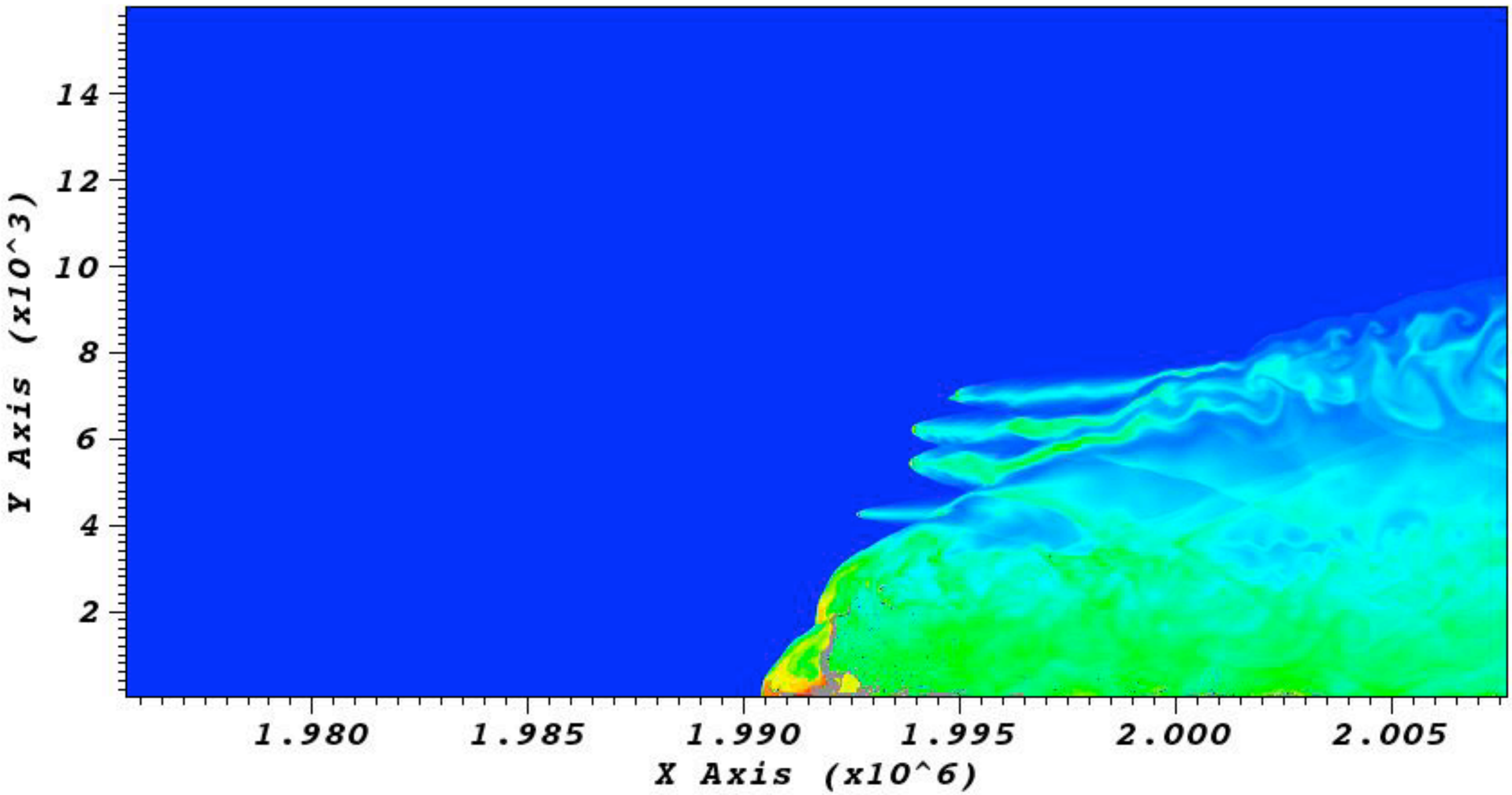

Lundstrom, E. and Anderson, T., "Hydraulic Ram Model for High Explosive Ammunition", ASME Pressure Vessels and Piping Conference, 1989

# Break-up

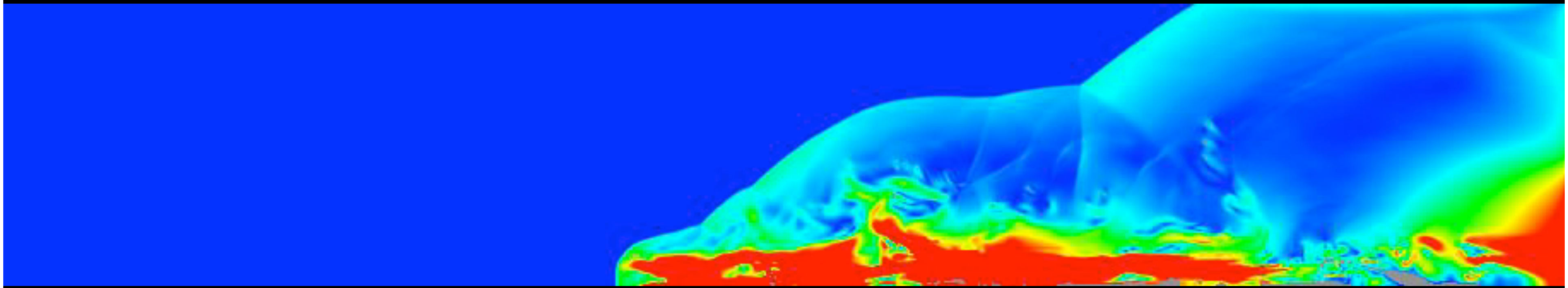


3.0
2.0
1.0
Y Axis (x10^3)
2.8910
2.8920
2.8930
2.8940
2.8950
2.8960
2.8970
2.8980
X Axis (x10^6)

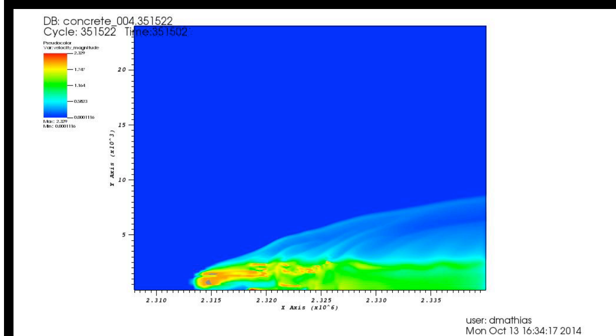
# Break-Up (Wider View)

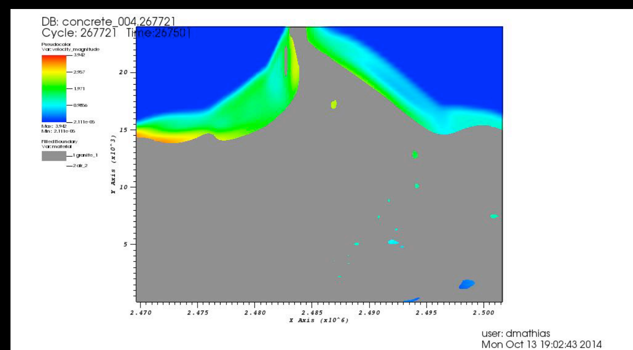


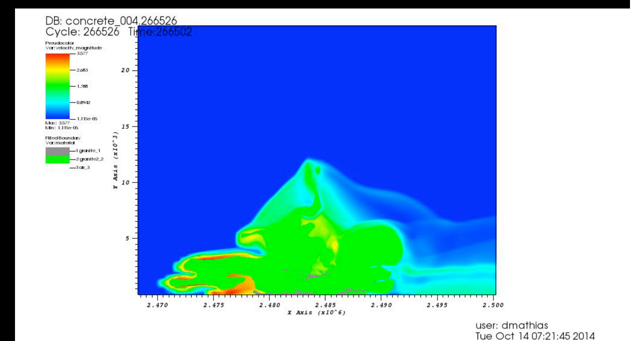
# Blast Wave



# Forcing Burst

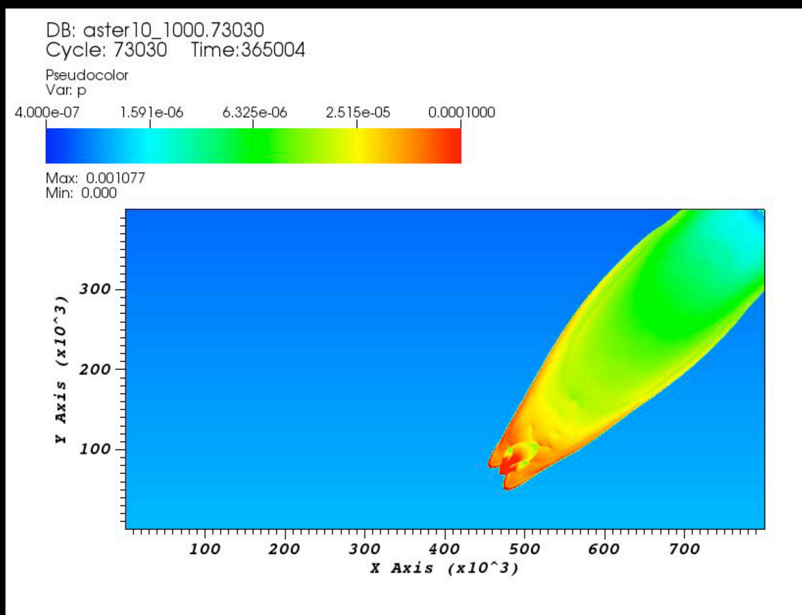


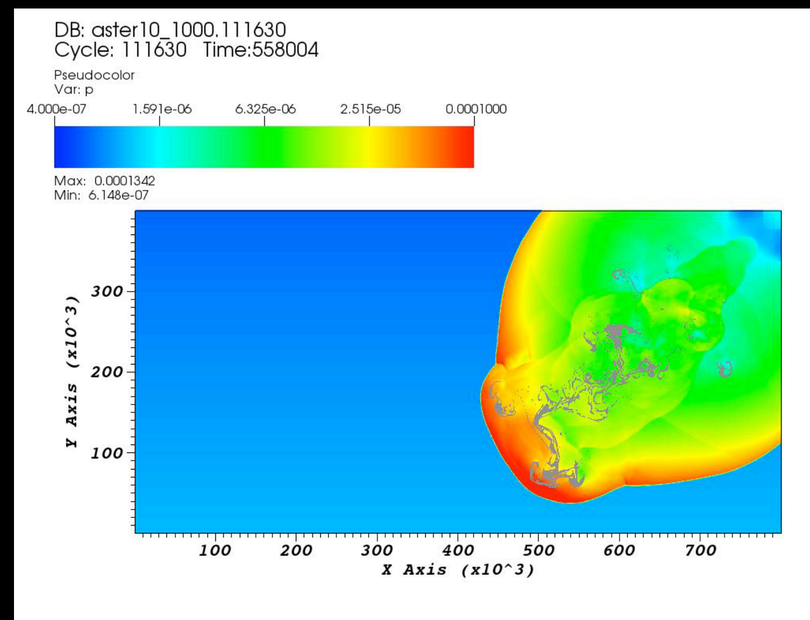




- Mechanical Only
- 5% Energy Added Uniformly
- 5% Energy Added to a few locations in the Asteroid

# Energy addition ± Fracture

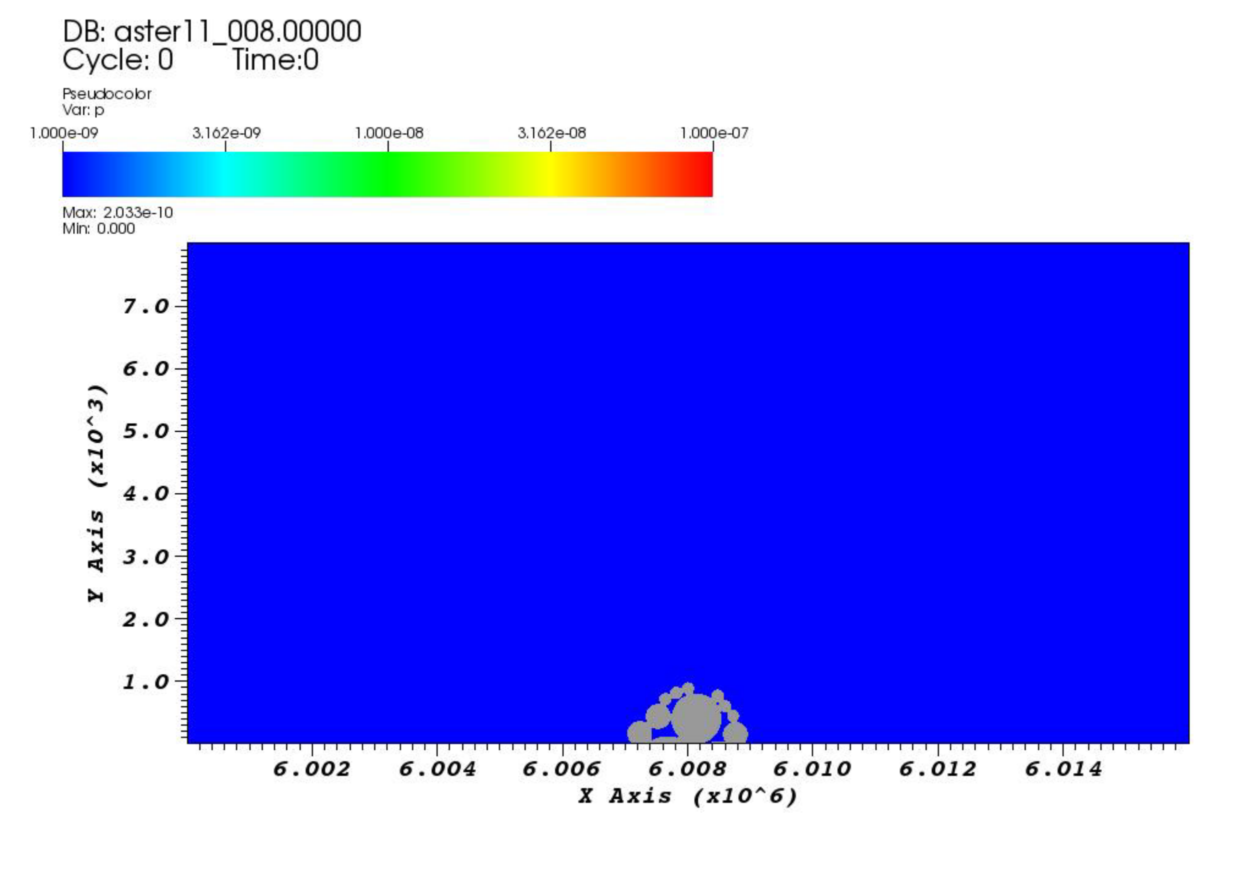



- 10% energy addition
- No fracture mechanism

- 50% energy addition
- Fracture modelled

# Rubble Pile




- Modelled Eulerian
- Change to Lagrangian to prevent merging of boulders
- Fill void space with regolith (porous, no strength, rock “dust”)

# Simple ALE3D Model

- Initial assumptions
  - Ideal gas atmosphere
  - Homogeneous generic rock with low fracture strength

# Future ALE3D Work

Link to/from TPS branch simulations?

- Improved Atmosphere Model
  - Multi-component mixture ($O_2$, $N_2$, etc)
  - Dissociation and Ionization in shock/boundary layer
  - Improved convective and radiative heat transfer
- Improved Asteroid Model
  - Improved fracture and porous crush models
  - Inhomogenous mixtures (Iron, Stone, Ice)
  - Melting and vaporization
  - 3D: Variation in shape and composition, tumbling
- Higher resolution on asteroid (Chimera grids)

Link to/from CART3D?

- Tracking of blast/shockwaves